

K^* nucleon hyperon form factors and nucleon strangeness

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Abstract

A crucial input for recent meson hyperon cloud model estimates of the nucleon matrix element of the strangeness current are the nucleon–hyperon– K^* (NYK^*) form factors which regularize some of the arising loops. Prompted by new and forthcoming information on these form factors from hyperon–nucleon potential models, we analyze the dependence of the loop model results for the strange–quark observables on the NYK^* form factors and couplings. We find, in particular, that the now generally favored soft $N\Lambda K^*$ form factors can reduce the magnitude of the K^* contributions in such models by more than an order of magnitude, compared to previous results with hard form factors. We also discuss some general implications of our results for hadronic loop models.

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I. INTRODUCTION

Understanding the non-valence quark content of hadrons remains, despite a history spanning over two decades, a major theoretical challenge. The interest in non-valence physics derives mainly from the unique opportunities which it provides for new insights into quantum aspects of hadron structure beyond the naive and spectroscopically very successful quark model. Important questions in this realm include modifications of the QCD vacuum inside hadrons [1], the mechanism of flavor mixing and the origin of the OZI-rule [2,3], the structure of constituent quarks [4], and the role of gluons in the dynamics of the (isoscalar) strange-quark sea in the nucleon [5].

The strangeness distribution inside of the nucleon [6] represents the most intensely studied example of a hadronic non-valence quark effect. Currently the vector channel of this distribution, as described by the strange vector form factors, is a focus of experimental [7–9] and theoretical [6,10] research. Since systematic and model-independent approaches have still little predictive power for the nucleon’s strangeness content (as exemplified by studies in chiral perturbation theory [11–14] and on the lattice [15]), most previous and current theoretical analyses of the strangeness form factors were model-based.

Among the first and most transparent models for the vector form factors were those which implement a kaon-cloud of the nucleon [16] and thus complement pole dominance approaches [17]. In kaon-cloud models the nucleon’s strangeness distribution is generated by fluctuations of the “bare” (i.e. nonstrange) nucleon into kaon-hyperon intermediate states which are described by the corresponding one-loop Feynman graphs [16]. The two crucial assumptions underlying the loop model are 1) that the lightest valence-strangeness carrying intermediate states generate the dominant contribution to the strangeness content and hence give at least a rough estimate of its size, and 2) that rescattering (i.e. multi-loop) contributions are suppressed (despite large couplings).

Both of these assumptions have recently been challenged. A dispersive analysis on the basis of analytically continued $K - N$ scattering data demonstrated that rescattering corrections are important even at low momentum transfers, both to restore unitarity and to build up resonance strength in the ϕ meson region [18]. Furthermore, a study in an “unquenched” quark model found the contributions from higher-lying intermediate states (up to surprisingly large invariant masses) indispensable for the calculation of the strange quark distribution [3] and prompted our collaborators and us to investigate these issues in a complementary hadronic one-loop model [19]. In addition to the original $K - Y$ loops ($Y = \Lambda, \Sigma$), we included the next higher-lying intermediate states, i.e. the $K^* - Y$ pairs. In the first part of this study the corresponding loops were evaluated using Bonn-Jülich K^*NY form factors (see below), as in the original $K - Y$ model. The results were discouraging: the K^* contributions were found to be larger than those from the kaon loop, and their dispersive analysis indicated strong unitarity violations.

The anomalously large and apparently unrealistic K^* contributions could be traced to the large K^* tensor couplings and, in particular, to the very large cutoff parameter of the $K^*N\Lambda$ form factor taken from the Bonn-Jülich potential model [20]. Since both the Nijmegen potential [21,22] and the forthcoming update of the Bonn-Jülich NY potential [23] find substantially smaller values for this cutoff, we feel that a detailed and quantitative analysis of the cutoff (and coupling) dependence of the K^* contributions (covering the whole

range of so far proposed values) would be a useful contribution to the ongoing discussion [24,25] of hadron loop model applications to nucleon strangeness. Such an analysis is one of the main objectives of the present paper. Furthermore, we will calculate and discuss the momentum dependence of the strange vector form factors in the loop model at low momentum transfers ($Q^2 \leq 1$ GeV) relevant for the present and planned measurements at MIT-Bates, TJNAF and MAMI.

II. THE MESON-HYPERON LOOP MODEL

We begin by recapitulating the definition of the strange vector form factors, the pertinent features of the hadronic loop model [16], and its extension to additional intermediate states containing K^* mesons [19]. The focus of our investigations will be on the nucleon matrix element of the strangeness current, which is parametrized by two invariant amplitudes, the Dirac and Pauli strangeness form factors $F_{1,2}^{(s)}$,

$$\langle N(p') | \bar{s} \gamma_\mu s | N(p) \rangle = \bar{U}(p') \left[F_1^{(s)}(q^2) \gamma_\mu + i \frac{\sigma_{\mu\nu} q^\nu}{2m_N} F_2^{(s)}(q^2) \right] U(p) . \quad (1)$$

Here $U(p)$ denotes the nucleon spinor and $F_1^{(s)}(0) = 0$, due to the absence of an overall strangeness charge of the nucleon. The leading nonvanishing moments of these form factors are the Dirac and Sachs (square) strangeness radii

$$\langle r_s^2 \rangle_D = 6 \frac{d}{dq^2} F_1^{(s)}(q^2) \Big|_{q^2=0} , \quad \langle r_s^2 \rangle_S = 6 \frac{d}{dq^2} G_E^{(s)}(q^2) \Big|_{q^2=0} , \quad (2)$$

as well as the strangeness magnetic moment

$$\mu_s = F_2^{(s)}(0) . \quad (3)$$

(The Sachs radius is obtained from the electric Sachs form factor $G_E^{(s)}(q^2) = F_1^{(s)}(q^2) + q^2/(4m_N^2) F_2^{(s)}(q^2)$ and related to the Dirac radius by $\langle r_s^2 \rangle_S = \langle r_s^2 \rangle_D + 3\mu_s/(2m_N^2)$.)

As mentioned above, we have chosen a hadronic one-loop model containing K and K^* mesons as the dynamical framework for the calculation of these moments. This model is based on the meson-baryon effective lagrangians

$$\mathcal{L}_{MB} = -g_{ps} \bar{B} i \gamma_5 B K \quad , \quad (4)$$

$$\mathcal{L}_{VB} = -g_v \left[\bar{B} \gamma_\alpha B V^\alpha - \frac{\kappa}{2m_N} \bar{B} \sigma_{\alpha\beta} B \partial^\alpha V^\beta \right] , \quad (5)$$

where B ($= N, \Lambda, \Sigma$), K , and V^α are the baryon, kaon, and K^* vector-meson fields, respectively, $m_N = 939$ MeV is the nucleon mass and κ is the ratio of tensor to vector coupling, $\kappa = g_t/g_v$. In order to account for the finite extent of the above vertices, the model includes form factors from the Bonn-Jülich $N - Y$ potential [20] at the hadronic KNY and K^*NY ($Y = \Lambda, \Sigma$) vertices, which have the monopole form

$$F(k^2) = \frac{m^2 - \Lambda^2}{k^2 - \Lambda^2} \quad (6)$$

with meson momenta k and the physical meson masses $m_K = 495$ MeV and $m_{K^*} = 895$ MeV [26]. These form factors render all encountered loop integrals finite and reproduce the on-shell values of the mesonic couplings. The range of currently favored values for the couplings g_{ps}, g_v, κ and cutoff parameters Λ_K and Λ_{K^*} , as well as their impact on the strangeness observables, will be discussed below.

Since the non-locality of the meson-baryon form factors (6) gives rise to vertex currents, gauge invariance was maintained in [19] by introducing the photon field via minimal substitution in the momentum variable k [27]. (Consequences of the non-uniqueness of this prescription are discussed in Refs. [27–29].) The resulting nonlocal seagull vertices are given explicitly in [19].

The diagonal couplings of $\bar{s}\gamma_\mu s$ to the strange mesons and baryons in the intermediate states are straightforwardly determined by current conservation, i.e. they are given by the net strangeness charge of the corresponding hadron. The situation is more complex for the non-diagonal (i.e. spin-flipping) coupling $F_{KK^*}^{(s)}(0)$ of the strange current to K and K^* , which is defined by the transition matrix element

$$\langle K_a^*(k_1, \varepsilon) | \bar{s}\gamma_\mu s | K_b(k_2) \rangle = \frac{F_{KK^*}^{(s)}(q^2)}{m_{K^*}} \epsilon_{\mu\nu\alpha\beta} k_1^\nu k_2^\alpha \varepsilon^{*\beta} \delta_{ab} \quad (7)$$

(where a and b are isospin indices and ε^β is the polarization vector of the K^*). This coupling was estimated in [19] on the basis of the vector meson dominance model of Ref. [30], with the result $F_{KK^*}^{(s)}(0) = 1.84$.

The relevant one-loop Feynman graphs of the model are completely determined by the above vertices and the standard meson and baryon propagators. The diagrams containing strange mesons fall into three categories, corresponding to fluctuations of the nucleon into either $K-Y$ or K^*-Y pairs, or to the strangeness-current induced spin flip transition from a $K-Y$ to a K^*-Y intermediate state. The explicit expressions for the corresponding loop amplitudes are collected in Appendix A. In the following calculations we will concentrate on the Λ contributions and omit the comparatively negligible Σ contribution [16,19].

III. INTERNAL HADRONIC VERTICES

In this section we investigate the dependence of the loop-model results on the couplings and cutoffs which parametrize the internal $K(K^*)\Lambda N$ vertices. In our previous analysis [19] we have used the ($SU(3)$ based) couplings $g_{ps}/\sqrt{4\pi} = -3.944$, $g_v/\sqrt{4\pi} = -1.588$, $\kappa = 3.26$ and the cutoff parameter values $\Lambda_{K^*} = 2.2$ (2.1), $\Lambda_K = 1.2$ (1.4) GeV of the Bonn-Jülich NY potential [20]. The cutoffs were determined from hyperon-nucleon scattering data, with the numbers in parenthesis denoting values obtained in an alternative model for the baryon-baryon interaction.

The numerical results of the loop model [19] are summarized in Table I. A glance at these numbers shows that the magnitude of the K^* contributions exceeds those of the K contributions by factors of 5–10. As already mentioned, the main reason for these unrealistically large contributions can be traced to the unusually large $K^*N\Lambda$ cutoff parameter $\Lambda_{K^*} = 2.2$ GeV found in [20]. It has twice the size of the typical hadronic scale ~ 1 GeV around which such cutoff parameters lie normally. A substantially larger value (which in

our case also exceeds the largest hadron masses in the loops by a factor of two) must be considered suspect in any model with hadronic degrees of freedom since one expects their quark–gluon substructure to become relevant at such scales.

Indeed, the appearance of anomalously large cutoffs in a potential model suggests that those cutoffs are burdened with short–distance physics (not directly related to the K^* sector) which would otherwise remain unaccounted for. Literally taking such effects over to the loop–model estimates of the nucleon’s strangeness content, by fully associating them with the physical K^* , would therefore very likely be misleading. A hint that the K^* sector of the original Bonn–Jülich potential might indeed be overburdened can be obtained from a comparison with the conceptually similar Nijmegen NY potential [21,22]. The Nijmegen potential contains more degrees of freedom in the scalar meson sector (including a pomeron) and finds a much smaller K^* cutoff $\Lambda_{K^*} \simeq 1.2$ GeV. Moreover, a smaller K^* cutoff is also favored in the forthcoming update of the Bonn–Jülich potential [23]. The K^* cutoff of this model is expected to lie around 1.5 GeV [31].

Hence, nowadays smaller cutoffs seem to be consistently favored by NY potential models. This motivated our reanalysis of the loop–model results of Ref. [19] for the nucleon’s strangeness observables (as also suggested in [25]) which we will discuss below. To get a qualitative idea of the range of coupling and cutoff values to be considered, and to maintain the underlying philosophy of the loop model, we will orient ourselves at the values used in the existing potential models. Of course, these values depend to some extent on the particular dynamics and particle content of a given model, and since the various potential models and also our model differ in this respect, the corresponding parameter sets cannot be directly compared or strictly related to each other. However, we expect the parameter ranges considered below, in particular for the cutoffs, to cover most of the physically reasonable parameter space of our model.

We begin our discussion of the parameter dependence by documenting the sensitivity of the results to variations in the cutoff. To this end, we display the cutoff dependence in the range $1\text{GeV} \leq \Lambda_{K^*} \leq 2.5\text{GeV}$, which covers all so far proposed values for Λ_{K^*} . The first two figures show the behavior of the Dirac strangeness radius (Fig. 1a) and the strangeness magnetic moment (Fig. 1b) as a function of Λ_{K^*} , with the K^* couplings fixed at the old, $SU(3)$ –based Bonn–Jülich values given above. The full curves show the total results, the dashed ones represent the $K^*K^*\Lambda$ contributions, the dash–dotted ones the $KK^*\Lambda$ contributions, and the dotted curve corresponds to the result from the K loop. Clearly, the cutoff dependence is very pronounced, reducing e.g. the value of Ref. [19] for the magnetic moment by almost an order of magnitude for $\Lambda_{K^*} \simeq 1.5$ GeV. The reduction is even considerably stronger for the Nijmegen value $\Lambda_{K^*} \simeq 1.2$ GeV.

Although a strong cutoff dependence was to be expected (especially due to the enhanced degree of divergence of the K^* loops with derivative couplings), its actual magnitude is still surprising. If cutoff sizes of the order of that used in the Nijmegen potential were to be the most realistic, some of the conclusions reached in [19] would have to be revised. In particular, for cutoffs of the Nijmegen size some sort of “convergence” of the intermediate–state sum (to one loop) could not anymore be excluded. In this case the kaon cloud contribution might well be sufficient for a first orientation about the overall size of the nucleon’s strangeness content in hadronic one–loop models, as advocated in [25] and in contrast to the findings of Ref. [3] in the quark model. Other problematic aspects of hadron–loop models, such as the

expected importance of rescattering corrections and unitarity violations [18], are of course not affected by these arguments.

The strong cutoff dependence of the strangeness observables exposes another, both conceptual and practical problem of hadronic loop models. Although the cutoff is principally a physical parameter (which indicates up to which resolution a purely hadronic description might be adequate), the foundations of the approach are not solid enough to give it a precise and quantitative meaning. Moreover, the available NY scattering data do not allow an accurate determination of the K^*NY form factors even in the framework of a specific potential model, not to mention other sources of uncertainty as, for example, the largely uncontrolled off-shell ambiguities incurred by transplanting such form factors into another model context. As a consequence, the numerical value of the K^* cutoff cannot be accurately determined, and the corresponding uncertainty propagates, amplified by a heightened sensitivity, into the strangeness observables. These facts already imply that at most semi-quantitative predictions can be expected from the hadron-loop approach.

The existing NY potential models differ not only in the momentum dependence of the K^*NY form factors, but also in the values of the corresponding K^* couplings. The K^* vector (Dirac) coupling of the Nijmegen potential is, for example, considerably smaller than the one of Ref. [20] which we used above. In order to illustrate the dependence of the strange form-factor moments on these couplings, we compare in Fig. 2 the K^* contributions to the strangeness radius (Fig. 2a) and magnetic moment (Fig. 2b) for the five pairs $(-1.588, 3.26)$, $(-0.8, 2.0)$, $(-0.8, 4.0)$, $(-2.0, 2.0)$, $(-2.0, 4.0)$ of coupling values $(g_v/\sqrt{4\pi}, \kappa)$. The first of these pairs corresponds to the values of Holzenkamp et al. while the others were chosen to encompass the range of values which appear in other potential models. The Figs. 2 a,b demonstrate that the variations of the strangeness observables due to different choices for the couplings can be quite substantial for large values of the K^* cutoff. The sensitivity to the couplings remains fairly small, however, for Λ_{K^*} of the order of 1 GeV, in particular for the strange magnetic moment and for couplings in the range between the Bonn-Jülich $(-1.588, 3.26)$ and Nijmegen [22] $(-1.45, 2.43)$ values¹.

Throughout all of the above calculations we have kept the values of Ref. [20] for the cutoff and coupling of the kaon fixed. The Nijmegen potential uses a pseudovector coupling which cannot be related without off-shell ambiguities to the pseudoscalar coupling of the Bonn-Jülich potential. On-shell, the equivalent pseudoscalar coupling of the Nijmegen potential ($g_{ps}/\sqrt{4\pi} \simeq -4.0$) differs by less than 5% from the Bonn-Jülich coupling used here, and the Nijmegen cutoff parameter $\Lambda_K \simeq 1.28$ GeV [22] is similarly close to the one we use. In any case, the cutoff and coupling values from potential models should not be taken too literally since, as discussed above, the limited available data and the implicit model assumptions do not allow their precise (and unique) determination.

We close this section with a remark on alternative choices for the internal form factors. The Bonn monopole form factors (6) have two well-known limitations: an artificial zero for cutoffs of the size of the meson mass (due to on-shell normalization) on which we will

¹These Nijmegen couplings are obtained from Table II of Ref. [22] by using the SU(3) relations given in their Eq. (2.14).

comment in the next section, and an unphysical singularity at time-like momenta $q^2 = \Lambda^2$. Although the singularity can be tamed by the usual causal boundary condition, it will still affect the values of the loop amplitudes to a certain extent. This problem could be avoided, although at the price of additional model dependence, by choosing alternative, singularity-free extrapolations of the Bonn form factors into the time-like region. One such extrapolation was proposed in Ref. [32].

IV. MOMENTUM DEPENDENCE OF THE STRANGE FORM FACTORS

All of the currently running or planned experiments measure the strange vector form factors at $Q^2 \neq 0$. Therefore, their data need to be extrapolated in order to obtain the leading form-factor moments. This extrapolation requires information on the momentum dependence of the form factors (at low energies) and thus on the spatial strangeness distribution inside the nucleon. In the following section we will evaluate the loop-model predictions for the momentum dependence by extending the above calculations to momentum transfers $Q^2 \leq 1 \text{ GeV}^2$. Both strange vector form factors will be measured in about the same Q^2 -range by the planned spectrometer experiment G0 at Jefferson Lab [9].

In the loop model, the coupling of the strange current to hyperon, meson, $K(K^*)NY$ vertex or K/K^* transition vertex inside the loop is described by corresponding vertex functions, which we list in the appendix. These vertex functions contain the full momentum dependence of the form factors and can be evaluated numerically. Fixing the cutoffs for the K^* and the kaon at $\Lambda = 1.2 \text{ GeV}$ and using the Nijmegen values for the coupling, we show in Fig. 3 (solid line) the resulting strange magnetic form factor

$$G_{SAMPLE}^{(s)}(Q^2) = G_M^{(s)}(Q^2) = F_1^{(s)}(Q^2) + F_2^{(s)}(Q^2). \quad (8)$$

together with the data point measured by the SAMPLE experiment at $Q^2 = 0.1 \text{ GeV}^2$ [7]. (For comparison we have also included the older data point from the first runs only.) Figure 4 (solid line) shows the loop-model prediction for the combination

$$G_{HAPPEX}^{(s)}(Q^2) = G_E^{(s)}(Q^2) + 0.39G_M^{(s)}(Q^2), \quad (9)$$

measured by the HAPPEX collaboration, together with their data point at $Q^2 = 0.48 \text{ GeV}^2$ [9]. The corresponding loop-model results for the Dirac strangeness radius and magnetic moment are given in Table I.

At first sight, the results are in disagreement with both the SAMPLE and the HAPPEX data. The measured form factor combinations are both positive (at their respective momentum transfers) while the loop model leads to negative form factors of smaller slopes and magnitudes. In particular, the loop model predicts - like the majority of the other so far investigated models - a small and negative value for the strangeness magnetic moment.

With regard to the SAMPLE result, however, there is a caveat. The derivation of the strangeness form factor from the measured asymmetry requires knowledge of the neutral weak axial form factor $G_A^{(Z)}$ of the nucleon and, in particular, its isovector radiative correction [10]. The newest published value $G_{SAMPLE}^{(s)}(Q^2 = 0.1 \text{ GeV}^2) = 0.61 \pm 0.17 \pm 0.21$ is based on the theoretical estimate [33] for this radiative correction, which carries a substantial amount

of uncertainty. The SAMPLE collaboration is currently measuring with a deuterium target [34] in order to pin down the axial weak form factor contribution separately. Only after taking these data or more accurate and reliable theoretical estimates into account (which could substantially change the quoted value for $G_{SAMPLE}^{(s)}(Q^2 = 0.1 \text{ GeV}^2)$ both in sign and magnitude) can the strange magnetic moment be extracted unambiguously and compared to the small value of the loop-model prediction.

Furthermore, it is interesting to note that the results of the loop model could be made consistent with the HAPPEX data by allowing for smaller cutoff values, as suggested by recent applications of the meson cloud model to deeply inelastic scattering [36,37]. In order to illustrate this point, we show in Figs. 3 and 4 (dashed lines) the results obtained by using $\Lambda = 0.9 \text{ GeV}$, which also brings the magnetic form factor somewhat closer to the SAMPLE data point. Moreover, this cutoff value is very close to the K^* mass and therefore effectively switches off the internal K^* form factors (cf. Eq. (6)). As a consequence, the contributions from the K^* and the K/K^* transition are completely negligible relative to the kaon contribution. This shows that the K^* contributions worsen the agreement of the loop model predictions with the current experimental results. However, the zeros of the Bonn form factors have to be regarded as artefacts of the on-shell normalization and the results for the small cutoffs should therefore be viewed with caution. The latter reservations are enhanced by the difficulties with the physical interpretation of cutoffs of the same size as particle masses in a loop.

In Figs. 5 and 6 we show the K , K^* and K/K^* transition contributions to the Dirac ($F_1^{(s)}$) and Pauli ($F_2^{(s)}$) form factors separately (again for $\Lambda = 1.2 \text{ GeV}$ and Nijmegen couplings). These figures demonstrate that even with the new values for cutoffs and couplings adopted in the present paper, the K^* and K/K^* contributions are still of the same order of magnitude as the kaon contributions. This is in contrast to the much smaller size of these contributions to the strangeness magnetic moment in the chiral quark model [35]. In the latter the tensor coupling of the K^* to the quarks is small, while the contributions from the vector coupling partially cancel each other and become proportional to the difference between the light and strange quark constituent masses, and therefore also small.

Finally, we present the loop-model result for the form-factor combination

$$G_{MAMI}^{(s)}(Q^2) = G_E^{(s)}(Q^2) + 0.22G_M^{(s)}(Q^2) \quad (10)$$

which the forthcoming MAMI A4 experiment [8] plans to measure at $Q^2 = 0.23 \text{ GeV}^2$. We find

$$G_{MAMI}^{(s)}(Q^2 = 0.23 \text{ GeV}^2) = \begin{cases} -0.012 & \text{for } \Lambda = 0.9 \text{ GeV} \\ -0.046 & \text{for } \Lambda = 1.2 \text{ GeV} \end{cases} \quad (11)$$

where the same reservations as above apply to the smaller cutoff value.

V. SUMMARY AND CONCLUSIONS

To summarize, we have analyzed the cutoff, coupling, and momentum dependence of the K^* contributions to the nucleon's vector strangeness content in the hadronic one-loop model

of Ref. [19]. It turns out that the softer K^*NY form factors now generally favored by NY potential models have some welcome consequences for such models. First, they can reduce the K^* contributions to the strangeness radius and magnetic moment by over an order of magnitude, thereby indicating that the contributions from the lightest KY intermediate states might be sufficient for rough estimates of the strangeness content in one-loop models. Although the K^* contributions remain non-negligible (in particular towards larger momentum transfers) and worsen the agreement with the data of the HAPPEX experiment, they cease to be unrealistically large and they do not anymore exclude some sort of (slow) “convergence” of the intermediate state sum. The very sensitive dependence of the results on the K^* cutoff emphasizes, however, the limited and mostly qualitative character of hadron-loop model predictions.

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APPENDIX A: VERTEX FUNCTIONS

In the loop model of section II the strangeness form factors receive four distinct types of contributions. Three of them correspond to amplitudes associated with processes in which the current couples either to the hyperon line (Y), the meson line (M), or the meson-baryon vertex (V) in the loop. The fourth contribution corresponds to the amplitude associated with the strangeness-current induced spin-flip transition from K to K^* . The corresponding vertex functions are

$$\Gamma_\mu^{(Y)}(p', p) = iQ_Y \int \frac{d^4k}{(2\pi)^4} \left[g_v^2 (F(k^2))^2 D^{\alpha\beta}(k) \left(\gamma_\alpha + i \frac{\kappa}{2m_N} \sigma_{\alpha\nu} k^\nu \right) S(p' - k) \gamma_\mu S(p - k) \times \right. \\ \left. \left(\gamma_\beta - i \frac{\kappa}{2m_N} \sigma_{\beta\gamma} k^\gamma \right) - g_{ps}^2 (F_K(k^2))^2 \Delta(k^2) \gamma_5 S(p' - k) \gamma_\mu S(p - k) \gamma_5 \right] , \quad (\text{A1})$$

$$\Gamma_\mu^{(M)}(p', p) = -iQ_M \int \frac{d^4k}{(2\pi)^4} \left[g_v^2 F((k+q)^2) F(k^2) D^{\alpha\lambda}(k+q) D^{\sigma\beta}(k) (\gamma_\alpha + \right. \\ \left. + i \frac{\kappa}{2m_N} \sigma_{\alpha\nu} (k+q)^\nu) [(2k+q)_\mu g_{\sigma\lambda} - (k+q)_\sigma g_{\lambda\mu} - k_\lambda g_{\sigma\mu}] \times \right. \\ \left. S(p - k) \left(\gamma_\beta - i \frac{\kappa}{2m_N} \sigma_{\beta\gamma} k^\gamma \right) + g_{ps}^2 F_K((k+q)^2) F_K(k^2) \times \right. \\ \left. \Delta((k+q)^2) \Delta(k^2) (2k+q)_\mu \gamma_5 S(p - k) \gamma_5 \right] , \quad (\text{A2})$$

$$\begin{aligned}
\Gamma_\mu^{(V)}(p', p) = Q_M \int \frac{d^4 k}{(2\pi)^4} \left\{ g_v^2 F(k^2) D^{\alpha\beta}(k) \left[i \left(\frac{(q+2k)_\mu}{(q+k)^2 - k^2} (F(k^2) - F((k+q)^2)) \times \right. \right. \right. \\
\left. \left(\gamma_\alpha + i \frac{\kappa}{2m_N} \sigma_{\alpha\nu} k^\nu \right) S(p-k) \left(\gamma_\beta - i \frac{\kappa}{2m_N} \sigma_{\beta\gamma} k^\gamma \right) - \frac{(q-2k)_\mu}{(q-k)^2 - k^2} (F(k^2) + \right. \\
\left. - F((k-q)^2)) \left(\gamma_\alpha + i \frac{\kappa}{2m_N} \sigma_{\alpha\nu} k^\nu \right) S(p'-k) \left(\gamma_\beta - i \frac{\kappa}{2m_N} \sigma_{\beta\gamma} k^\gamma \right) \right) + \\
+ \frac{\kappa}{2m_N} \left(F((k+q)^2) \sigma_{\alpha\mu} S(p-k) \left(\gamma_\beta - i \frac{\kappa}{2m_N} \sigma_{\beta\gamma} k^\gamma \right) + \right. \\
\left. - F((k-q)^2) \left(\gamma_\alpha + i \frac{\kappa}{2m_N} \sigma_{\alpha\nu} k^\nu \right) S(p'-k) \sigma_{\beta\mu} \right) \left. \right] - i g_{ps}^2 F_K(k^2) \Delta(k^2) \times \\
\left[\frac{(q+2k)_\mu}{(q+k)^2 - k^2} (F_K(k^2) - F_K((k+q)^2)) \gamma_5 S(p-k) \gamma_5 \right. \\
\left. - \frac{(q-2k)_\mu}{(q-k)^2 - k^2} (F_K(k^2) - F_K((k-q)^2)) \gamma_5 S(p'-k) \gamma_5 \right] \left. \right\} , \tag{A3}
\end{aligned}$$

$$\begin{aligned}
\Gamma_\mu^{(K/K^*)}(p', p) = - \frac{g_v g_{ps} F_{K^*K}^{(s)}(0)}{m_{K^*}} \epsilon_{\mu\nu\lambda\alpha} \int \frac{d^4 k}{(2\pi)^4} \left\{ F((k+q)^2) F_K(k^2) D^{\alpha\beta}(k+q) \times \right. \\
\Delta(k^2) (k+q)^\nu k^\lambda \left(\gamma_\beta + i \frac{\kappa}{2m_N} \sigma_{\beta\delta} (k+q)^\delta \right) S(p-k) \gamma_5 + \\
+ F(k^2) F_K((k+q)^2) D^{\alpha\beta}(k) \Delta((k+q)^2) k^\nu (k+q)^\lambda \gamma_5 \times \\
\left. S(p-k) \left(\gamma_\beta - i \frac{\kappa}{2m_N} \sigma_{\beta\delta} k^\delta \right) \right\} . \tag{A4}
\end{aligned}$$

In the above equations we define $p' = p + q$ and use the notation $D_{\alpha\beta}(k) = (-g_{\alpha\beta} + k_\alpha k_\beta / m_{K^*}^2) (k^2 - m_{K^*}^2 + i\epsilon)^{-1}$ for the K^* propagator, $\Delta(k^2) = (k^2 - m_K^2 + i\epsilon)^{-1}$ for the kaon propagator, $S(p-k) = (\not{p} - \not{k} - m_Y + i\epsilon)^{-1}$ for the hyperon, Y , propagator with mass $m_\Lambda = 1116$ MeV. The strangeness charges are $Q_Y = 1$ and $Q_M = -1$ and $F(k^2)$, $F_K(k^2)$ refer respectively to the K^* and kaon form factors, both given by Eq.(6).

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TABLES

	$\langle r_s^2 \rangle_D$ (fm ²)		μ_s	
Λ (GeV)	1.2	2.2	1.2	2.2
$KK\Lambda$	-0.007		-0.237	
$K^*K^*\Lambda$	0.0023	0.030	-0.180	-4.149
$KK^*\Lambda$	0.0207	0.085	0.253	1.023

TABLE I. Intermediate state contributions to the strange magnetic moment μ_s and the electric strangeness radius $\langle r_s^2 \rangle_D$ in the loop model of [19].

FIGURES

FIG. 1. The dependence of a) the Dirac strangeness radius and b) the strangeness magnetic moment on the cut-off parameter of the $K^*N\Lambda$ form factor. The dashed (dot-dashed) line corresponds to the $K^*K^*\Lambda$ ($KK^*\Lambda$) contributions, the dotted line represents the kaon contribution, and the full line gives the total result.

FIG. 2. The dependence of a) the Dirac strangeness radius and b) the strangeness magnetic moment on the cut-off parameter of the $K^*N\Lambda$ form factor for different values of the $K^*N\Lambda$ couplings: $(g_v/4\pi, \kappa) = \{(-1.588, 3.26)$ solid line, $(-0.8, 2.0)$ dashed line, $(-0.8, 4.0)$ dot-dashed line, $(-2.0, 2.0)$ long-dashed line, $(-2.0, 4.0)$ dotted line $\}$.

FIG. 3. Strange magnetic form factor of the nucleon. The solid and dashed lines give the results using $\Lambda = 1.2$ GeV and $\Lambda = 0.9$ GeV respectively and the data points show the new and (for comparison) earlier results of the SAMPLE experiment [7].

FIG. 4. Strange electric and magnetic form factor combination as measured by the HAPPEX collaboration [9]. The solid and dashed lines give the results using $\Lambda = 1.2$ GeV and $\Lambda = 0.9$ GeV respectively.

FIG. 5. Strange Dirac form factor of the nucleon calculated using $\Lambda = 1.2$ GeV. The solid, dashed and dot-dashed lines give the kaon, K^* and K/K^* transition contributions respectively.

FIG. 6. Strange Pauli form factor of the nucleon calculated using $\Lambda = 1.2$ GeV. The solid, dashed and dot-dashed lines give the kaon, K^* and K/K^* transition contributions respectively.















